Data reconciliation of steam networks in refineries and petrochemical sites

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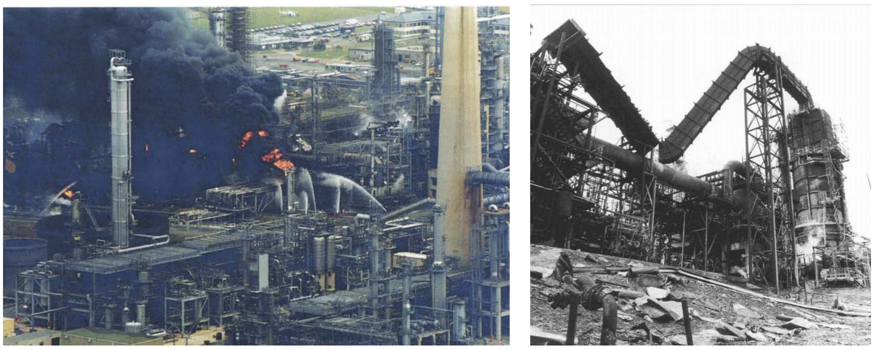
If you can not measure it, you can not improve it.

Lord Kelvin



(a) Fire (b) Aftermath

Figure 1: Pictures of the Texaco Refinery explosion and fire (a) and aftermath (b) in Milford Haven

1 Introduction

Process knowledge is the key factor in establishing quality energy efficiency and integration solutions. Without process knowledge, engineers run the risk of oversizing, undersizing or creating non-feasible and potentially dangerous solutions. Resulting accidents can have the potential to cause massive damage to infrastructure, lives and the environment, especially in the refining and petrochemical industries (which can include fertiliser production).

One example among many is that of the explosion and fire at the Texaco Refinery in Milford Haven on the 24th of July 1994, where hydrocarbons ignited and ripped through the flare drum outlet of the fluidised catalytic cracking unit. 26 refinery workers were injured and severe structural damage to the plant, the refinery and some buildings in Milford Haven ensued. The events took place following an electrical thunderstorm followed by sensor failures. Improper process modifications played an a priori part in the incident. the lack of process knowledge played in an important part in the escalation of the incident [1].

The fire and subsequent damage to the process unit can be seen in Figure 1. Improved process knowledge would have helped avoid this incident at all stages by carrying out safer process modifications, perhaps indicating that a sensor failure had taken place and certainly improved emergency management. According to the official investigation, a faulty sensor on a control valve indicated it as open when it was in fact shut. Had the operators had redundant or additional information to contradict this faulty sensor reading, they may have been able to reconcile the information leading to a different unfolding of events.

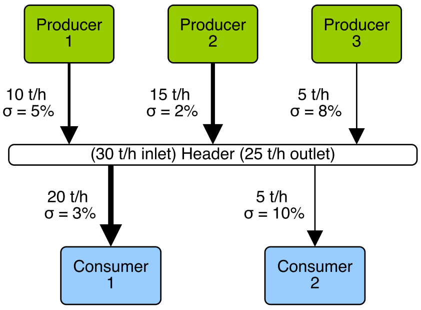
As the aim of this thesis is to establish optimisation methods for the utility networks of refining and petrochemical sites, namely the steam network, it is necessary to establish which actors are producing and consuming steam and with what properties to a high level of accuracy.

A fully functioning and well calibrated steam flowmeter may be accurate within a 4% range under nominal conditions. Higher accuracy flowmeters on transactionable flows such as feedstocks and hydrogen may be accurate to a 1%. Similarly, pressure and temperature gauges are only accurate to a certain degree. With such inaccuracies it is impossible to close mass balances through simple arithmetic, more advanced methods are required.

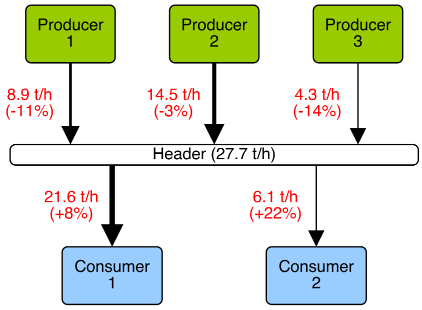
Measurement innacuarcy in steam networks stems mainly from unavoidable random and systematic errors [10]. The effect of systematic errors can be reduced by proper measurement device maintenance, though random errors are impossible to fully eliminate.

For operators, these relatively precise sensors and occasional gross errors may be sufficient to operate processes satisfactorily, though steam accounting would remain complicated. However, due to an important number of missing steam flow measurements, knowledge about the steam demand diminishes even further. In such situations, assumptions on the steam flow properties become necessary, making guesswork of mass and therefore energy balances.

Closing mass balances through gross mass balances may be considered a lesser evil than open mass balances, however one must be careful to distinguish 'known unknowns' from 'unknown unknowns', adding a



(a) Raw measures



(b) Reconciled measures

Figure 2: Example of mass balance closing through data reconciliation

level complexity that cannot be resolved with simple tools.

Operational optimisation studies require a high level of precision, as even a 1% energy cost reduction can lead to significant overall savings. In order to calculate and predict such an increment in efficiency, engineers must be able to ensure that improvements are not buried within the data's noise.

Similarly, infrastructure optimisation studies require precise data. The current economic and management context requires that energy efficiency projects have very short returns on investments, typically less than 2 years. To meet these conditions, engineers need precise costing and operational data.

In view of the above mentioned points, a method is required to improve the quality of measures, to validate or correct assumptions and provide more rigorous ways for estimating unknowns. Data reconciliation provides an elegant means of meeting these requirements. Data reconciliation was first developed by Kuehn and Davidson in 1961 [2] based on least squares principles. It was introduced to the process industry by Reilly and Carpani in 1963 [3], to improve material balances and therefore process knowledge. It has since become a time tested tool among the following industries:

1. Refineries, chemical, petrochemical, process: Improved process knowledge, product accounting, utility network accounting [4, 5, 6].

2. Oil and gas extraction: Improved estimation of reservoir sizes and multiphase flows (virtual flowmeters) [7].

3. Nuclear power plants: Ability to push steam turbine production to its upper limits through improved process knowledge, increased security through better process knowledge and added measurement redundancy[8].

Data reconciliation provides a mathematical method to modify measured values such as mass flows to solve mathematical equations, for example mass balances or chemical reactions. The mathematical equations provide inviolable rules to follow, while measured values are optimally modified to meet them.

An example is given in Figure 2 in which three producers of a certain substance feed two consumers through a closed header. The raw measures seen in (a) indicate that a total of 30 t/h is coming into the header while only 25 t/h is leaving. No other consumers or producers exist, measurement error is at cause. Equation 1 provides the physical laws F of the model.

$$\underbrace{\sum_{i=1}^{3} Producer_i - \sum_{i=1}^{2} Consumer_i}_{\text{F}} = 0 \tag{1}$$

In data reconciliation a new value y_i^* is associated to each of the n measurements y_i, so as to solve the system equations $F(\mathbf{x}, \mathbf{y}^*) = 0$, where x are the unknowns of the system. The system equations can include mass and energy balances, chemical reactions, stochastic relations or user defined equations.

Data reconciliation calculates y_i^* (as close to y_i as possible) by minimising equation 2 using a non-linear solver. This equation is also known as the penalty factor.

$$Obj = \min_{x,y^*} \sum_{i=1} (\frac{y_i^* - y_i}{\sigma_i})^2 \qquad s.t. \quad F(x, y^*) = 0 \tag{2}$$

High penalty factor values should be investigated and understood as they may result from bad modelling or gross errors. σ_i represents the uncertainty associated to measure y_i[1].

When data reconciliation is applied to the example, new values of the mass flows are calculated as seen in red in Figure 2 (b), with the relative change as a percentage in the brackets. As can be expected, values with the smallest σ_i had the smallest relative change (Producer 2), while those with larger ones had higher relative change (Consumer 2). The objective value (also know as penalty) was $Obj = 22.5$.

Data reconciliation problems must be redundant to solve unknowns and reconcile variables. This means that the number of equations must be equal to the number of variables. By providing the architecture of a steam network, many equations can be generated automatically, the aim being to match and even surpass the number of unknowns, strengthening the results of the reconciliation.

Rather than discussing the fundamentals of data reconciliation which have been amply covered, this report a systematic methodology to apply data reconciliation to the particularities of steam networks to the refining and petrochemical industries.

Section 2 describes typical data issues faced by these industries followed by their common causes in Section 3. The methodology for modelling and reconciling the steam network of a large industrial site can be found in Section 4.

2 Typical data issues

This section presents some typical data issues that may be encountered when working with industrial data and how they contribute towards open mass balances and therefore energy balances. The following examples are taken directly from raw industrial data.

2.1 Measurement errors

Figure 3 shows two readings of a transactional steam flow. As the steam is bought and sold, a measure is made by each actor in order ensure redundancy and oppose any eventual accounting irregularities. The graph in (a) shows both measurements while (b) shows the difference between Measurement 2 and 1 with an average value of 1.3 t/h. Some fairly significant differences (± 6.5 t/h) can also be seen at times.

Table 1 summarises the key thermodynamic and economic properties of Figure 3 considering a steam price of 18 $\$/t_{steam}$. As the steam flow is significant, a small measurement difference of approximately 2.5% in measured flowrate can lead to important accounting difference (205 $k\$$).

	Min [t/h]	Mean [t/h]	Max [t/h]	Yearly cost $[k\$/yr]$
Actor 1	8.0	50.7	112.2	7994.3
Actor 2	11.4	52.0	112.2	8199.4
Absolute difference	3.4	1.3	0.0	205.0

Table 1: Key properties of two sensors on same steam flowrate measurement device

These sorts of measurement differences also highlight that measurement devices are never fully accurate, but rather offer results within a certain range dependent on their characteristics.

[1] For a flat measure subjected only to random noise, σ_i can be chosen as its standard deviation, it can otherwise be based on user experience.

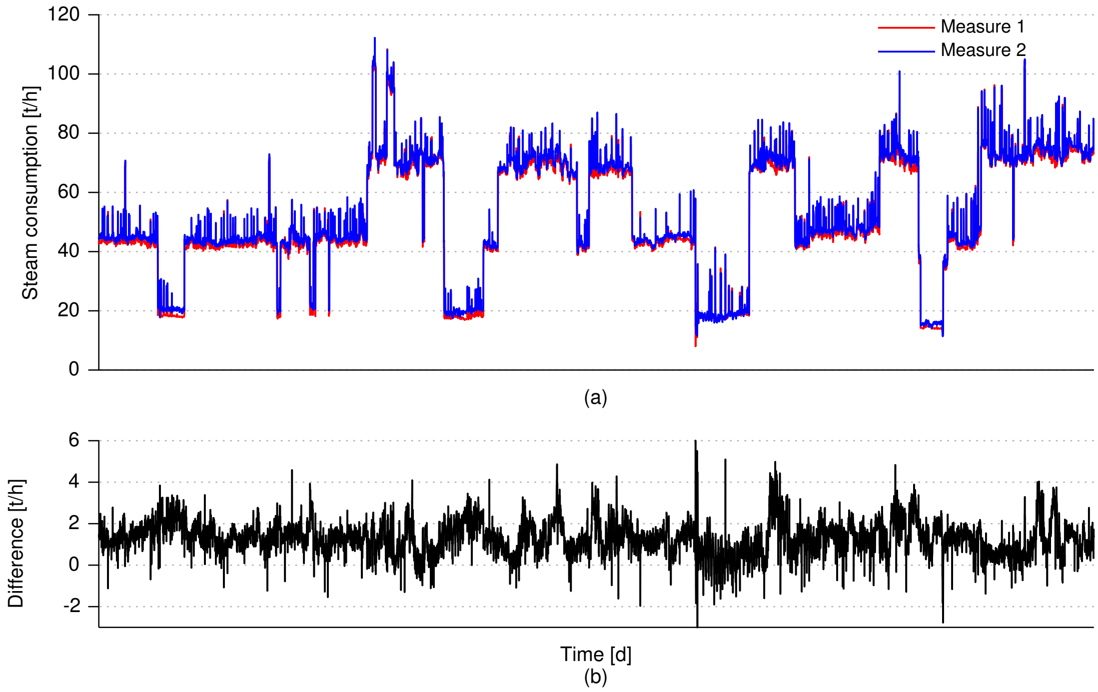


Figure 3: Example of measurement error on a single flow meter

2.2 False readings

Figure 4 shows the effects of calibration errors on measurements. In this example, the steam flow obviously surpasses the scale limit of the sensor. As such, a significant proportion of steam and therefore energy cannot be estimated properly.

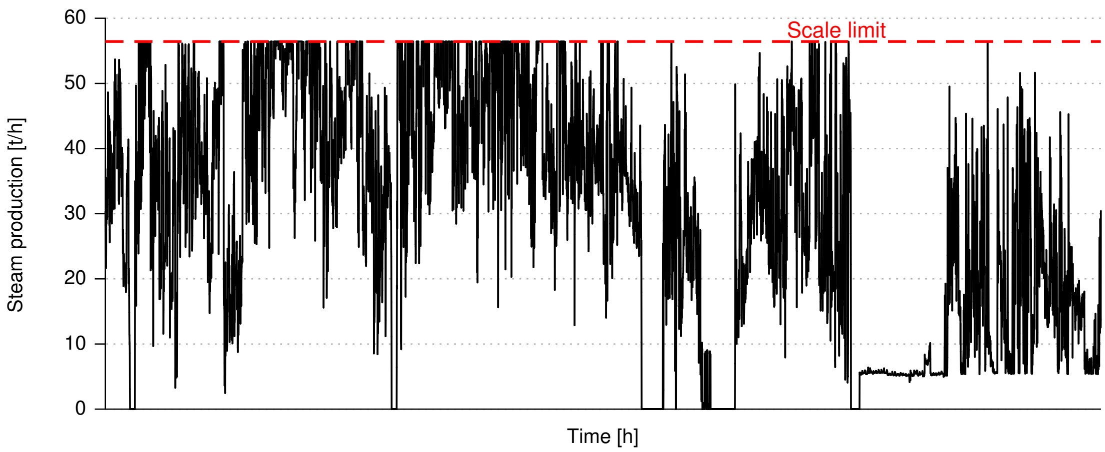


Figure 4: Example of an overscale measurement

Figure 5 shows another case of false readings in which steam is incorrectly attributed (and billed) to a process. Graph (a) shows the steam consumption of a heat exchanger over a year. Graph (b) shows the controller output of the control valve associated to the steam flowrate. Graph (c) shows the throughput of feedstock through the unit over a period of 41 days. The segment shown in red corresponds to a total process unit shutdown which lasted 10.5 days.

The figure shows that despite the process unit being completely shutdown, 1853 tons of steam are

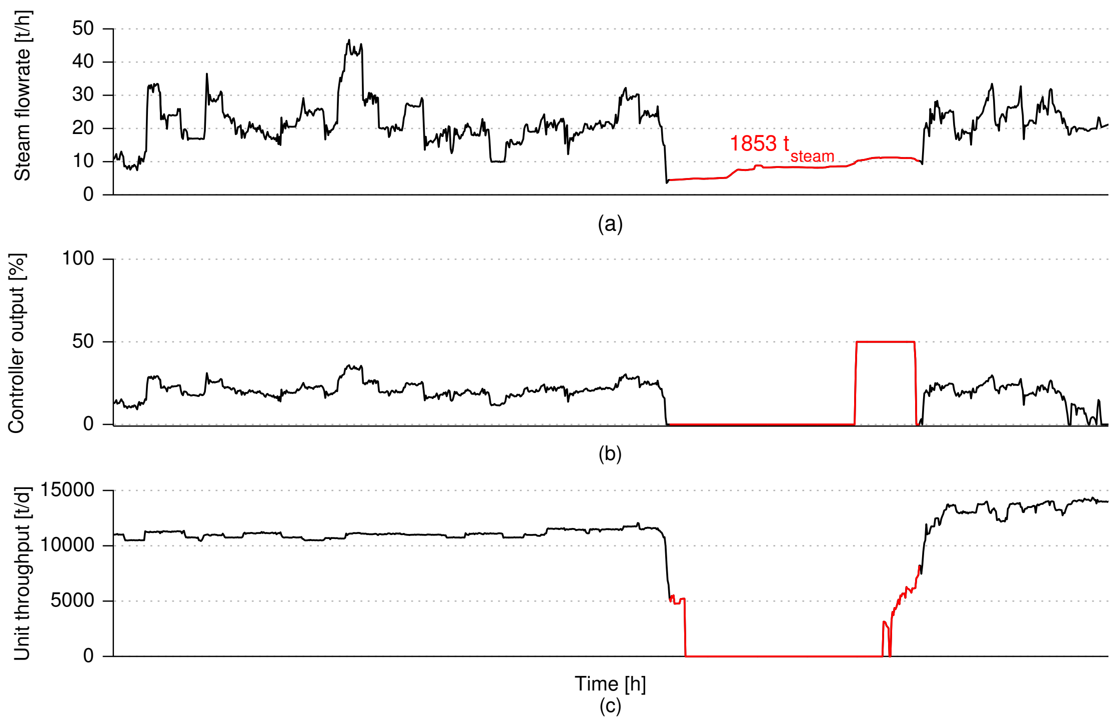


Figure 5: Example of the incorrect measurement of a steam flow process unit shutdown

incorrectly attributed to the heat exchanger over a period of 10.5 days, corresponding to 33 k$ (18 $\$/t_{steam}$). The process unit is billed for this steam (unless reconciliation takes place downstream) and energy studies may incorrectly consider this steam consumption. Such errors typically occur as a result of the behaviour of the sensor electronics.

2.3 Combined errors

Figure 6 shows the combined effects of missing measurements as well as random and systematic measurement errors. Graph (a) shows the inlet of steam into a header in red and the outlet in blue, while (b) shows the difference. In this header, all of the inlets and outlets of steam are measured, therefore the mass balance should theoretically close. In general the trends of the inlet and outlet are the same, though some gross errors do appear to be present.

Negative difference: Random errors (noise), systematic errors (calibration and sensor failures) are the major reasons for negative mass balance differences.

Positive difference: Losses (steam leaks and condensation losses) must be comparatively small in this example as the difference is rarely positive. The same applies to random errors. On the other hand, sensor failures are visible in the circled areas of (b). In the left circle, it appears that a steam consumer goes offline, while in the second circle out of scale inlet values are reported on two occasions, likely due to sensor malfunction.

3 Causes of data issues

Figure 6 highlighted that steam accounting problems do not simply lie with random and calibration errors. In a large steam network with hundreds of measuring devices, the combination of these errors are added

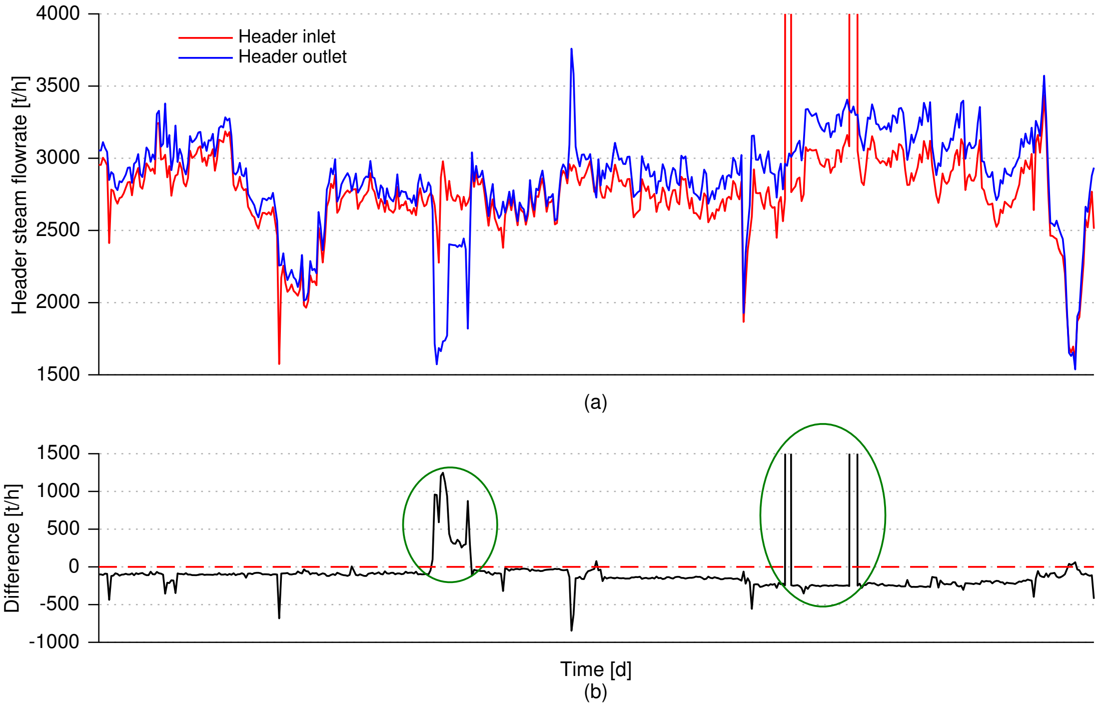


Figure 6: Example of the effect of combined errors on mass balances

to occasional (and occasionally undetected) sensor failures, large numbers of unmeasured consumers and system wide thermal and steam losses.

Three main causes for the identified data issues are discussed individually in this section:

- Large number of unmeasured consumers
- Inherently low measurement accuracy
- Losses

3.1 Unmeasured consumers

At the time of construction of the European sites, the price of fuel was considerably lower and operating margins were higher [11]. As such, steam was considered a 'cheap' utility to which only limited attention needed to be paid. Operators in these industries may still have not fully integrated the costs dimension of steam into their practices.

Given this perception of steam and the high cost of measuring devices, their networks were not always defined in the interest of strict accounting, but rather to supply operators the flexibility they required to operate process units and utilities. [2]

For the above mentioned reasons, many steam consumers were left unmeasured. For example, letdowns were often left unmeasured as a simple mass balance could be made on the header to estimate their flowrates.

When constructed, steam networks with properly isolated pipes and well maintained steam traps were less subject to losses be they thermal or physical. With maintenance costs reduced and the risk of disappearing knowledge about the networks, older sites are sure to suffer from higher losses and operability issues.

[2]It should be noted that even in our current climate (focused on energy efficiency) it would not be reasonable to measure each of the many hundred steam consumers, but better control could easily be applied.

3.1.1 Letdowns

Flowrates through letdowns are often left unmeasured, as they are not considered as steam consumers, only transporting steam across pressure levels. As a consequence, steam headers often lack enough measurements to be redundant.

Though steam flows through letdowns are rarely measured, the demineralised water injected through the desuperheaters is at times measured. If the temperatures and pressures of the inlet and outlet steam are measured, as well as the demineralised water flow, the initial letdown flow can be back calculated.

3.1.2 Turbines

Unlike letdowns, turbines are prised for their ability to produce mechanical work, to power electricity generators, fans, pumps or compressors. Larger turbines are usually measured as their produced work can be considered critical. Their flows are measured to add a source of redundancy to the operating system.

On the other hand, smaller turbines (for example turbo-pump and turbo-compressor) complexes are often left unmeasured or are coupled together.. Within process units, turbines are generally not measured. Samples can be however be obtained on their activation rates (if the system is automated) and their nominal flowrates, meaning that average steam flow can be estimated.

3.1.3 Consumers

Given the very large number of small steam consumers on industrial sites, it would be prohibitively expensive to measure all of them. These 'known unknowns' include:

- Utility tracing: to keep fluids from congealing. Design values may give an estimate of the flowrates, though this information can often be hard to find.

- Small heat exchangers: process information can be used to back calculate steam flows. For example, if the process fluid composition and properties are known, the amount of heat exchanged and therefore the steam quantity can be calculated.

- Occasional use heat exchangers: heat exchangers only used at process startups, shutdowns or under specific and occasional circumstances. Their flowrates may simply not be worth calculating, as they are often manually activated with relatively small flowrates.

'Unknown unknown' steam consumers pose another problem. Take the example of a steam hose used to keep equipment warm in winter. These hoses are manually activated and can be left activated for unknown periods of time. Neglect of these uncounted numbers of devices makes calculating their flowrates very challenging.

3.1.4 Producers

Most steam producers are measured as their flowrates are usually significant. If they are not measured, process data can be useful for calculating the steam flows.

The case of flash steam from recovered medium pressure condensates is challenging as the flowrates are generally not measured. If the properties of the condensates are measured (which is usually not the case) the amount of flash steam can be calculated. Otherwise assumptions can be made to estimate the flowrate, with fairly low accuracy.

3.2 Low measurement accuracy

While electricity is simple to measure to a high degree of accuracy, the same does not apply for steam or gases as they are compressible and subject to change according to pressure and temperature. Orifice plate devices make up the large majority of the steam flowmeters in the refining and petrochemical industry, while the more accurate vortex flowmeters are usually used for transactionable flows.

Measurement devices inherently suffer from random and systematic errors described below, as do their sensors and the entire metering system. Proper maintenance can reduce the effects of errors, for example in orifice plate devices where the sharp of the orifices edges are blunted with time leading to reduced accuracy[12].

3.2.1 Random errors

Random errors are ever present and unpredictable in all measuring devices. While random errors should not affect the accuracy of steam measures averaged over large periods, as their averages are usually nil. In high accuracy work, random errors tend to gain importance. they will bring errors in the case of smaller time steps.

3.2.2 Systematic errors

A systematic error is "*a persistent statistical error having a nonzero mean that cannot be attributed entirely to chance but to inaccuracy inherent in the statistical system*"[13]. Though their importance may vary, systematic errors can skew and shift data, with nonzero means, making mass balances complicated to calculate, even when using lengthy time averages.

These may include calibration errors (leading to a positive or negative shift in measured values, Figure 3) and multiplier effects where data readings no longer correlate with real data. As pressures, temperatures and densities may change in certain flows, flowmeters must be calibrated accordingly[14].

Electronic sensors are calibrated for specific operating ranges and will give gross errors outside of those ranges. Figure 4 showed the effect of overscale measurements.

The turndown ratio of orifice plate flowmeters are said to be between 5:1 and 3:1, meaning that their measures are only reliable if above 20-33% of the nominal flowrate. Their accuraciesra range between 2-4% of the nominal rate[15]

3.3 Steam losses

3.3.1 Condensation losses

A functioning steam trap will evacuate condensates when they accumulate within pipes. On the other hand, a broken steam trap may evacuate no steam evacuate steam constantly. It is difficult to know whether or not a steam trap is working properly as in either case steam is vented to the atmosphere. Proper maintenance operations are therefore necessary to manually inspect steam traps.

Extreme weather events such as heavy rains can lead to significantly increased condensation losses, as the ground on which pipes are installed can be flooded. In such cases, pipes can be completely submerged and substantially cooled.

3.3.2 Steam leaks

Steam leaks are inevitable though they may be addressed through proper maintenance. The larger the industrial, the more significant the proportion of steam losses will be as networks become harder and more expensive to manage.

4 Steam network data reconciliation

Given the very large number of flows and recorded thermodynamic properties in large industrial sites, a systematic methodology is required to accelerate the modelling and reconciliation process, without affecting the quality of the measured data. The aim of data reconciliation being to improve the accuracy of measures, the resolution of the data used must be high as well.

Some general properties to be applied to measures and assumptions are detailed below followed by typical cases to be encountered when modelling a steam network.

4.1 Data gathering

The architecture of the steam network must be acquired and modelled for reconciliation to be effective. This information can be obtained in Process Flow Diagrams (PFDs), Process Instrumentation Diagrams (PIDs) and flowdiagrams. PIDs are important as they supply the data codes of the flowrate, temperautre and pressure measurements which can then be extracted from data systems.

Security and operator manuals are particularly useful. Security manuals often detail equipment properties (heat exchangers, vessels, boilers,...). Operator manuals provide descriptions of operations which can clarify the uses of equipments.

A tour of the steam network and discussion with operators is highly recommended to identify the following:

- Missing consumers
- Undocumented or unindentified modifications to the steam network
- Steam leaks
- Steam traps
- Condensate returns (not always indicated on PFDs and PIDs)

4.2 General properties of measures

Each flowrate, pressure or temperature measure, y, can be analysed to determine it nominal value $\bar{y}$ to which a standard uncertainty $\bar{\sigma}$ can be attributed. High pass, low pass and cutoff filters can be applied to measures, with standard values detailed in Table 2. These are based on user experience and should be adapted to each problem.

4.2.1 High pass filters

Each measure (flowrate or thermodynamic property) y should be subject to a high pass filter, equation 3, to avoid overscale readings (as seen in Figure 4). The high pass values y_{max} should be determined through a Data Analysis (DA) and operator knowledge. Typical values are presented in 2.

$$\text{If} \quad y > y_{max} \Rightarrow \sigma = \sigma_{max} \tag{3}$$

4.2.2 Low pass filters

Lowpass filters can limit the innaccuracies associated to flows below their turndown rates, Equation 4. Typical values are presented in 2.

$$\text{If} \quad y < y_{low} \Rightarrow \sigma = \sigma_{low} \tag{4}$$

	$\bar{\sigma}$ [%]	σ_{max} [%]	y_{max} [M.U.]	σ_{low} [%]	y_{low} [M.U.]	y_{min} [M.U.]	y_{forced} [M.U.]
Orifice plate	8	15	DA	30	$0.25\times\bar{y}$	$0.1\times\bar{y}$	0
Vortex	4	8	DA	8	$0.15\times\bar{y}$	$0.05\times\bar{y}$	0
Temperature	2	10	DA	–	–	25°C	$\bar{y}$
Pressure	2	2	DA	–	–	DA	$\bar{y}$

Table 2: Standard properties for filters when modelling steam networks.

4.2.3 Cutoff filters

Cutoff filters can also be used to force values to zero to eliminate obviously erroneous sensors as seen in Figure 3, equation 5. Other data can be used to reinforce the cutoff filters, such as unit throughput. In the case of temperature and pressure measurements, typical values can be applied to y_{forced} to avoid skewing thermodynamic data in a posteriori averages. Typical values are presented in 2.

$$\text{If} \quad y < y_{min} \Rightarrow y = y_{forced} \quad \& \quad \sigma = 0 \tag{5}$$

4.3 General properties of assumptions

Assumptions can be improved by coupling them to existing information, such as unit throughput.

The uncertainty values σ associated to each assumption must be adapted according to the available information. For the example of a measured process heated by an unknown amount of steam, the steam consumption can be estimated to a reasonable accuracy through the process fluid composition, pressures, flowrate and inlet and outlet temperatures.

Some typical values used in assumptions are given in the modelling cases below, though these should always be adapted with care.

4.4 Modelling cases

Figure 7 provides a schematic for types of cases to be faced when modelling a large industrial site's steam network. Each case is described. Black colors depicts measured quantities while red shows the unmeasured ones to be calculated or estimated. While these descriptions are general, they are in no way exhaustive as several alternative ways exist to calculate steam flows through headers, heat exchangers, letdowns and turbines.

In reconciliation, redundancy provides improved results, therefore as much pertinent information as possible should be included in a model while respecting some rules of thumb on data acquisition such as the 80/20 rule [16].

4.4.1 Case 1 – Steam header

Steam headers should be subject to the following modelling rules.

1. Mass balance.
2. Energy balance.
3. Temperature equality between all outlet streams, unless contradictory information exists.
4. Zero pressure drop across the header, unless contradictory information exits.

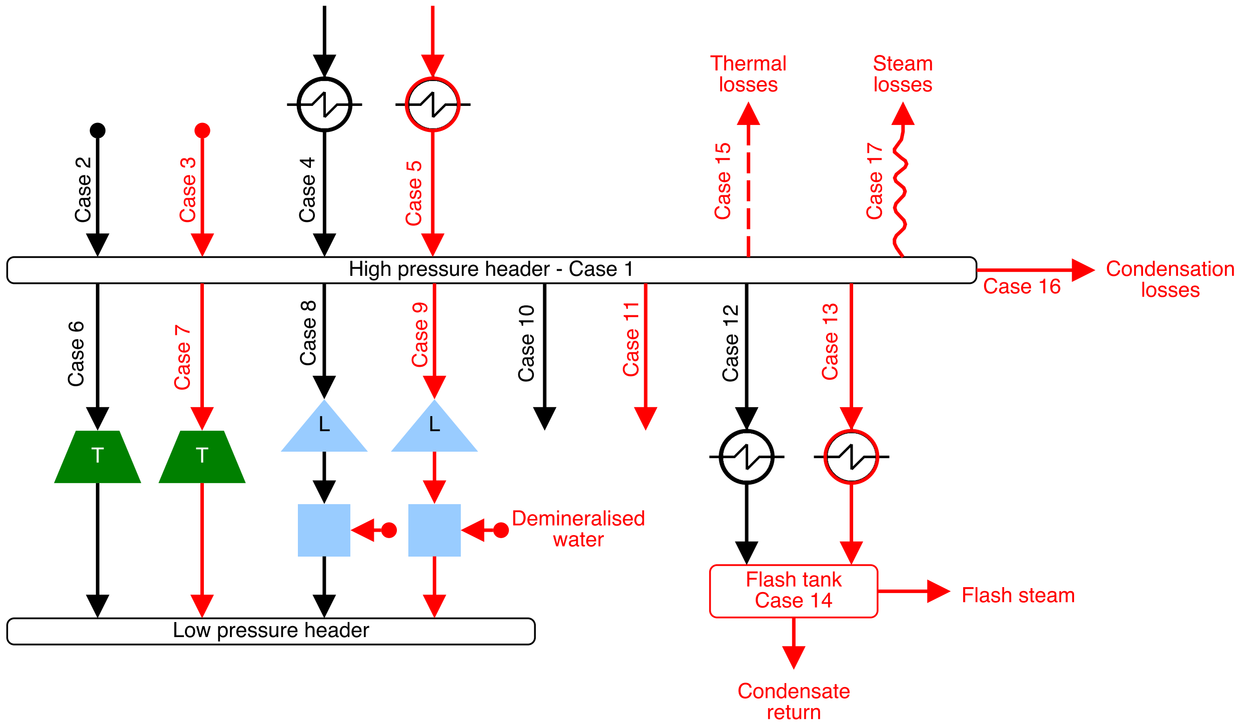


Figure 7: Typical cases when modelling and reconciling a large industrial site's steam network.

Steam is mostly superheated and therefore can be defined by its pressure level, temperature and flowrate. Partially condensed steam should not theoretically exist if the steam traps operate properly, though it can occur in practise. In such a case, modelling becomes very complicated as it is not possible to easily calculate the vapour fraction. Using a vapour fraction of 100% and the saturation temperature of the steam can be a solution.

With the above modelling rules, pressure and temperature measurements can be limited to a minimum. In effect, inlet flows will often inherit their pressures and temperatures from upstream headers while outlet flows will inherit these properties thanks to points 3. and 4.

4.4.2 Case 2 – Measured steam inlet

Possible measurements and design values:

- Steam: temperature, pressure and flowrate

If the steam flow is connected to an upstream header, the flowrate should be sufficient to model it, as its pressure and temperatures will be inherited automatically. Otherwise, these must be defined. Assumptions on the temperature may be difficult to make without other information, while the pressure can be assumed to be that of the header as the data reconciliation will correct it. If such is the case, the uncertainty of the pressure reading must be relatively high, e.g. $\sigma_{pressure} = 10\%$.

4.4.3 Case 3 – Unmeasured steam inlet

Possible assumption and design values:

- Steam: pressure and temperature,

In the absence of flowrate measurements, design data should be used to quantify it, associated to a very large uncertainty, for example $\sigma_{flowrate} = 30\%$.

4.4.4 Case 4 – Measured steam generation

Possible measured and design values:

- Steam: temperature, pressure and flowrate
- Process: temperature, pressure, flowrate, composition

Several cases can be considered for measures steam generation.

- **Boilers:** Modelling of steam boilers can contribute towards highly accurate measurements of the production. The boiler presented in Figure ??. As the demineralised water network is usually measured as well, the information adds important redundancy to the steam flow calculation. Furthermore several key performance indicators can be calculated and reconciled as a result, such as the energy efficiency, economiser heat recovery, O_2 content and temperature of the fumes.
- **Saturated steam:** These heat exchangers can be assumed to produce 100% saturated steam, thus defining their temperatures with respect to the pressure. If pressure measurements are not available assumptions can be made, though care should be taken to make sure that pressure is equal to or higher than the header pressure. If measures are available on the process side of the exchanger, data can be used to further reconcile the steam measure.
- **Superheated steam:** High temperature heat sources can be used to evaporate and then superheat steam. As above, a pressure measure or assumption is required. The superheating temperature should also be measured.

4.4.5 Case 5 – Unmeasured steam generation

Possible assumptions and design values.

- Steam: temperature, pressure and flowrate
- Process: temperature, pressure, flowrate, composition

In the absence of measures on the steam flow, process side measurements can be used to calculate the energy load delivered to steam. If no process information, design information can be used if available. Without this data a statistical analysis can be carried out on the header to estimate its flowrate. If it is considered to be important, it is recommended to carry out manual measures to better understand the flowrates.

4.4.6 Case 6 – Measured turbine flow

Possible measures and design values.

- Steam inlet: temperature, pressure and flowrate
- Steam outlet: temperature, pressure
- Turbine: isentropic efficiency, minimum and maximum flowrates
- Generator: electricity production, conversion efficiency

If the flowrate of a turbine is measured, complimentary measured or design data may help further reconcile values.

- Isentropic efficiency $\eta_{turbine}$: this value should be supplied by the turbine manufacturer, or can be calculated if the outlet steam temperature and pressure is known. Care should be taken to consider the conversion losses in the generator as well.
- Output temperature: this important value is easy to measure and can be used to strengthen the calculations on the power and efficiency of the turbine.
- Electrical power: for large turbines, this power is generally measured. The uncertainty on electrical measures will usually be very low, for example $\sigma_{power} = 1\%$.
- Output pressure: if unknown, it can be assumed to be that of the lower pressure header.

4.4.7 Case 7 – Unmeasured turbine flow

Possible assumptions and design values.

- Steam inlet: temperature, pressure and flowrate
- Steam outlet: temperature, pressure
- Turbine: isentropic efficiency
- Moved process fluid: inlet and outlet pressure, temperatures, composition
- Pump/compressor: isentropic efficiency

As is often the case for smaller turbo pump/fan/compressor complexes, let us consider that no measures are available on their flows. These turbines are either activated manually or remotely. Regardless, the design flowrate $\bar{f}_{turbine}$ and isentropic efficiency $\eta_{turbine}$ should be acquired.

- Manual activation: empirical rules should be established for the activation rate of the turbine $k_{turbine}$. Large uncertainty should be applied, for example $\sigma_{turbine} = 60\%$.
- Remote activation: if the turbine is remotely activated, the data system should store a record of its activation through time. This data can be sampled in order to obtain a mean activation rate $k_{turbine}$. Large uncertainty should be applied, for example $\sigma_{turbine} = 40\%$.

The outlet pressure of the steam can be assumed to be the lower header's pressure, while the outlet temperature will be calculated thanks to $\eta_{turbine}$. The flowrate of the turbine is estimated using equation 6

$$f_{turbine} = k_{turbine} \times \bar{f}_{turbine} \tag{6}$$

The reason for such high uncertainty despite the remote activation case stems from the lack of knowledge on the accuracy of $\bar{f}_{turbine}$.

If process information is available on the moved fluid (in the case of turbo compressors and turbo pumps), it can be used to help reconcile. Pressures at inlet and outlet, efficiency, fluid composition and flowrates from the pumps or compressors would be required or assocaited assumptions.

4.4.8 Case 8 – Measured letdown flow

Possible measures and design values.

- Steam inlet: temperature, pressure and flowrate
- Steam outlet: temperature, pressure

– Desuperheater: steam temperature setpoint, demineralised water flowrate, maximum flowrate

– Letdown: maximum flowrate

If a letdown is coupled to a desuperheater, it can be modelled by its flowrate, its inlet and outlet pressures and the desuperheating temperature (setpoint).The demineralised water flowrate can either be calculated or reconciled. Inversely, if the deminersalised water flowrate is available and the steam flowrate is not, it can be back calculated.

4.4.9 Case 9 – Unmeasured letdown flow

Possible assumptions and design values.

– Steam inlet: temperature, pressure

– Steam outlet: pressure

– Desuperheater: steam temperature setpoint, demineralised water flowrate, maximum flowrate

– Letdown: maximum flowrate

In the absence of measures, design values can be used to help calculate demineralised water flowrates, though the flowrate of steam can only be calculated by mass balance difference.

Letdowns are often left unmeasured due to their non critical nature, leading to non redundant measuring systems.

4.4.10 Case 10 – Measured steam outlet

Possible measures and design values.

– Steam: temperature, pressure, flowrate, minimum and maximum flowrates.

These fairly straightforward cases can be defined only by their flowrates as their temperatures and pressures should be inherited from the header.

4.4.11 Case 11 – Unmeasured steam outlet

Possible assumptions and design values.

– Steam: flowrate

These can for example include pipe tracing, storage tank tracing, turbine activation and steam hoses. As they can often be very difficult to estimate, large uncertainty should be associated, dependent on the quality of the design data.

Storage tank tracing loads can be estimated if the surface area and material of the tank are known, though accuracy will be fairly limited. The best practise is to combine all of these unmeasured steam outlets into a single steam consumer, in worst case with an unknown value. In this way, the massbalance on a header can be used to estimate its value.

4.4.12 Case 12 – Measured heat exchanger

Possible measured and design values:

- Steam: flowrate
- Condensate: temperature, pressure
- Process: temperature and pressure at inlet and outlet, flowrate, composition
- Heat exchanger: surface area, heat transfer coefficient, design load, log mean temperature difference

Complete information on a heat exchanger can be very useful when modelling steam networks as it will also bring about information on the condensate network, where significant energy and economic savings opportunities can exist.

Process information can be used to reconcile the steam measurement through energy load calculations. In turn, the condensate desuperheating temperature can be calculated, leading to higher accuracy in downstream calculations of flashed steam.

4.4.13 Case 13 – Unmeasured heat exchanger

Possible assumptions and design values:

- Steam: flowrate
- Process: temperature and pressure at inlet and outlet, flowrate, composition
- Process unit: throughput, production rate, activation rate
- Heat exchanger: surface area, heat transfer coefficient, design load, log mean temperature difference

In the absence of measured information, design values can be associated to the unit's activation rate to estimate the steam load. High uncertainty values should be chosen in such a case, for example $\sigma = 25\%$.

4.4.14 Case 14 – Unmeasured flash tank

Possible assumptions and design values:

- Condensate: flowrate (also equal to the steam consumption), temperature and pressure
- Low pressure header: steam pressure

The condensate flowrate, pressure and temperature must be known or estimated to calculate the quantity of flashed steam. If measures are not available for the flowrate, the quantity of consumed steam can be used. The condensate pressure and temperature can also be estimated using the upstream steam pressure of the steam. The steam can be assumed to condense and desuperheat 10 °C below its saturation temperature for example.

Once these properties are known, the quantity of flashed steam can be calculated through thermodynamic relations.

4.4.15 Case 15 – Thermal losses

As steam pipes are generally made of steal, thermal losses are ever present in industrial sites and manifest themselves by temperature loss and condensation of steam. If the flowrate of steam is known, the thermal losses can be estimated through the temperature differential between steam inlet and outlet, or by establishing the surface area and heat transfer coefficient of the pipes. The first method is possible only if the steam's temperature remains above the saturation temperature.

4.4.16 Case 16 – Condensation losses

The amount of condensed steam can be estimated based on design values of the steam network. The thermodynamic calculation is based on the diameter of the pipes, the grade of the steel, the insulation material and thickness, steam pressure and temperature.

Another method for estimating condensate losses consists in calculating mean steam trap flowrates based on their analysis (including malfunctioning traps). Once the mean steam trap flowrate T_s are established for each site s, the flowrate of condensed steam can be estimated using equation 7, where $n_{trap,s}$ is the number of steam traps in the industrial site.

$$f_{cond,s} = n_{trap,s} \times T_s \tag{7}$$

Regardless of the method used, the uncertainty associated to steam condensation must be high as it is impossible to confirm them without proper collection, maintenance and measurement. For example, $\sigma = 30\%$.

4.4.17 Case 17 – Steam leaks

Two methods exist to estimate the flowrate of steam through a leak.

1. The plume length can be estimated [17] Alternatively, the leak diameter can be measured and based on pressure difference calculations, the flowrate of a leak can be estimated. Leaks are rarely circular making this method complicated.

2. As steam leaks are generally numerous, obtaining such information can be very laborious. It is therefore recommended to perform an extensive survey and calculate mean flowrate of leaks per pressure level. Estimates can be made based on the total amount of steam leaks and their pressure levels, though an important number of man hours may be required to identify each leak, especially in large sites. These values should be updated regularly.

   Once the mean steam leak flowrates L_j are established for each site's pressure level j and the total number of leaks n_{leaks,h_j} per header h_j has been counted or estimated, the flowrate from leaks for each of the headers can be estimated using equation 8.

$$f_{leak,h_j} = n_{leak,h_j} \times L_j \tag{8}$$

Similarly to condensate losses, high uncertainty values must be used as the methods are very approximative, for example $\sigma = 50\%$.

4.4.18 Case 18 – Condensate return

Condensate returns are not always measured at process unit exit, though the overall return to the boilerhouse is often measured. With sufficient process knowledge, it can be established if a heat exchanger returns condensate. Such heat exchangers can be modelled and their condensate can be reconciled with the overall measure. In this way, it is possible to confirm/reconcile the amount of condensates returned by process units.

4.4.19 Case 19 – Measurement boundaries

It may be possible to provide boundaries for measurements based on process knowledge. For example, a boiler is rated for a maximum power which is theoretically not surpassable. An increase of a few percent beyond this limit may be possible, but no more. Similarly, a pipe of a given diameter will only be able to let so much steam through. This sort of information can strengthen a data reconciliation model, as it reduces the exploration space of the mathematical optimiser.

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